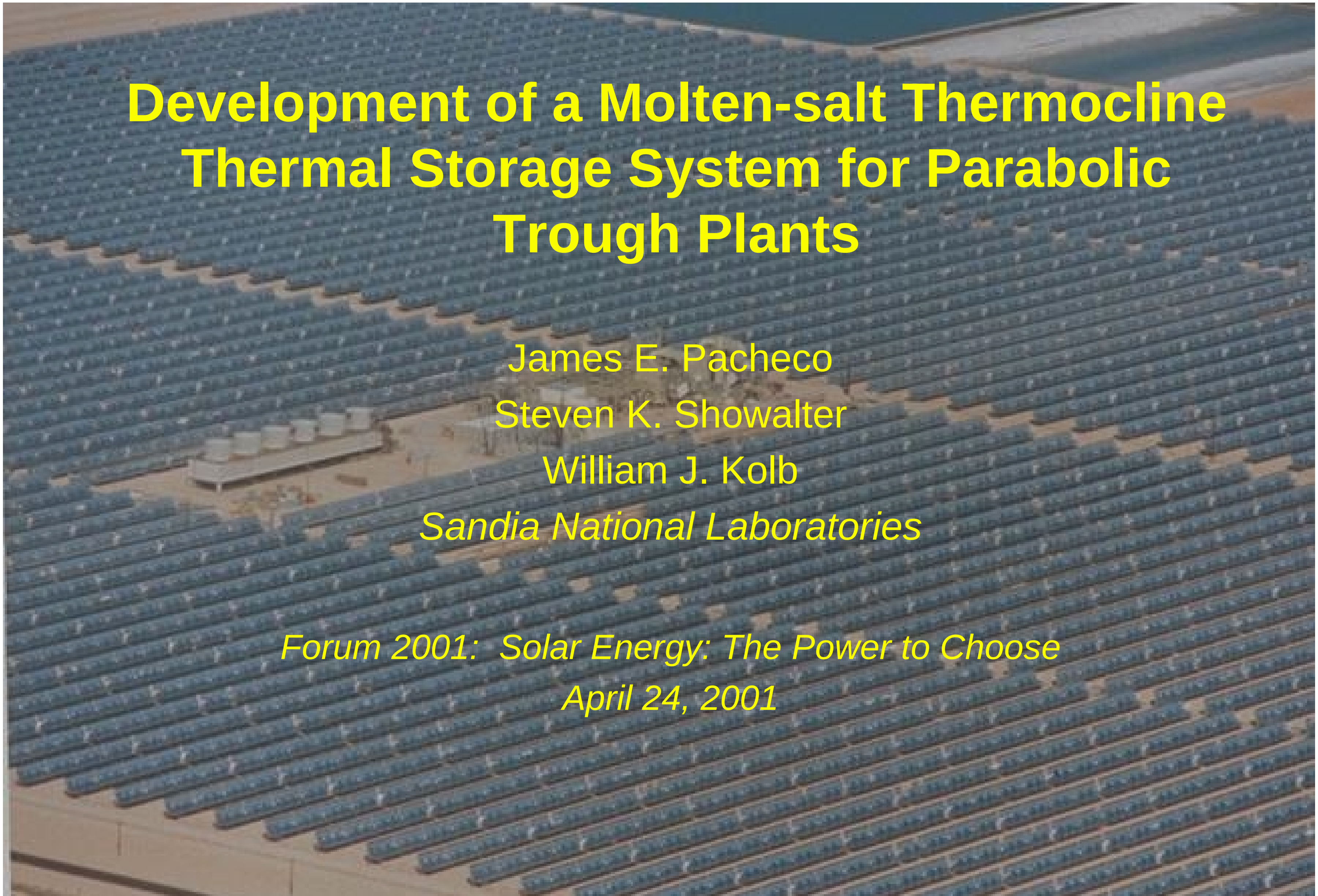

Development of a Molten-salt Thermocline Thermal Storage System for Parabolic Trough Plants

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Need for Thermal Storage for Trough Plants

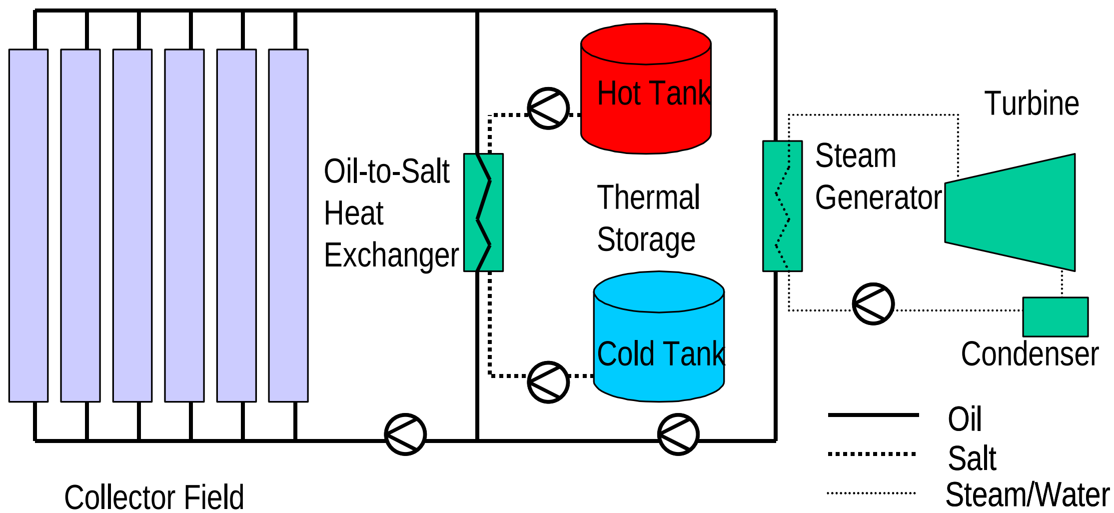
- Enables dispatchability without fossil fuel
- Provides load shifting
- Increases revenue from plants
- Allows higher solar fraction in combined cycle (CC) plants
- Improves economics of solar in CC plants
- Decouples collection from electricity production

How Thermal Storage Can be Integrated into a Solar Plant

- Direct
  - Heat transfer fluid is the same as the storage media
  - Examples: SEGS 1 (mineral oil), Solar Two (molten salt)
- Indirect
  - Heat transfer fluid is transferred to another media
  - Examples: SEGS plant (synthetic oil transfers heat to molten salt in a two tank system).

Estimated Capital Cost Of a Two-Tank Molten Salt System: $\$31/kWh_t$

Long-term Goal: $\$10/kWh_t$



Indirect Thermal Storage System

Objective of Thermocline Development Project

- *Reduce the capital costs of storage for parabolic trough plants relative to the baseline (indirect two-tank molten-salt system).*
- *Address the technical risks associated with thermocline storage:*
  - *Compatibility of filler materials with molten-salt*
  - *Unproven concept*
  - *Safety issues of fuel (Therminol) next to oxidizer (nitrate salt)*

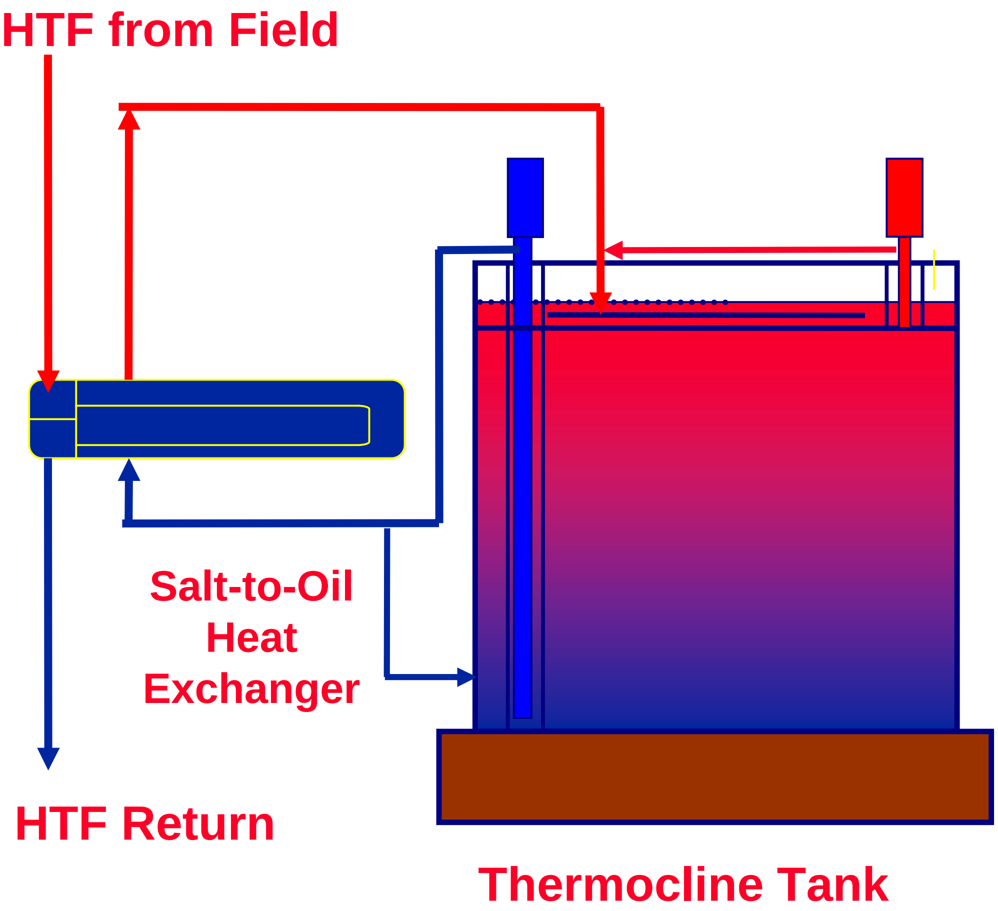
Description of Thermocline System

A thermocline molten salt system:

- Uses a single tank to storage energy

- Has a thermal gradient that separates the hot from cold fluid.

- Uses a low-cost filler material to displace higher-cost molten nitrate salt.



Development Activity Divided into 3 Areas

- Model thermocline system: Simulate performance and economics
- Evaluate candidate filler materials: Isothermal and thermal cycling tests
- Test a small pilot-scale thermocline: 2.3 MWh capacity to validate performance and operating characteristics

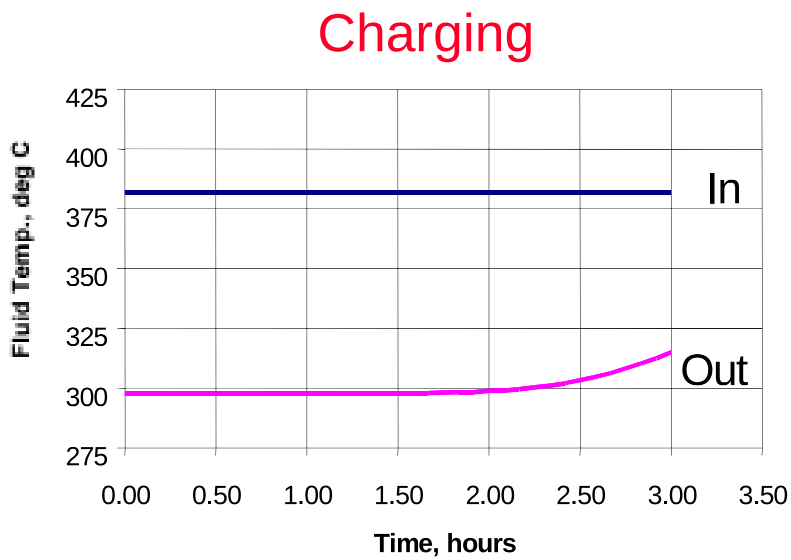
Modeling a Thermocline System

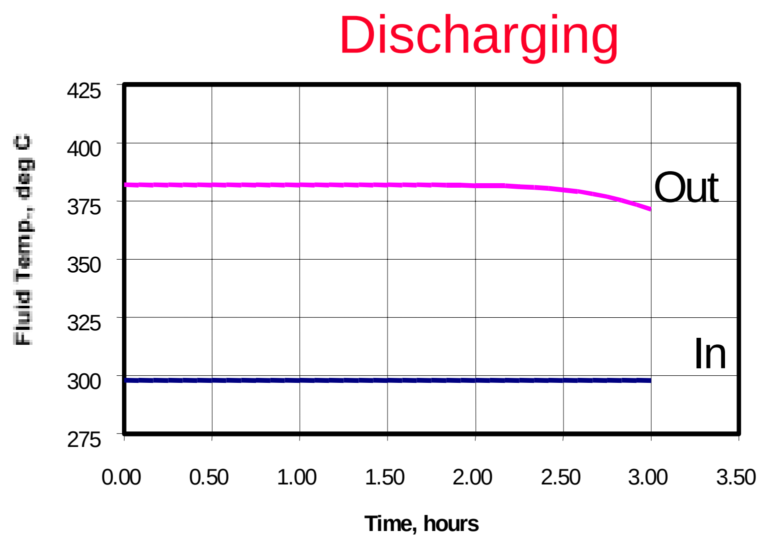
- Transient thermal behavior simulated by the Schumann equations which describe the heat transfer between a fluid and a packed bed.
- Finite difference representation of these equations enabled calculations of the thermal gradient and inlet and outlet temperatures as a function of time.
- Also enabled calculation of extracted energy and capacity.

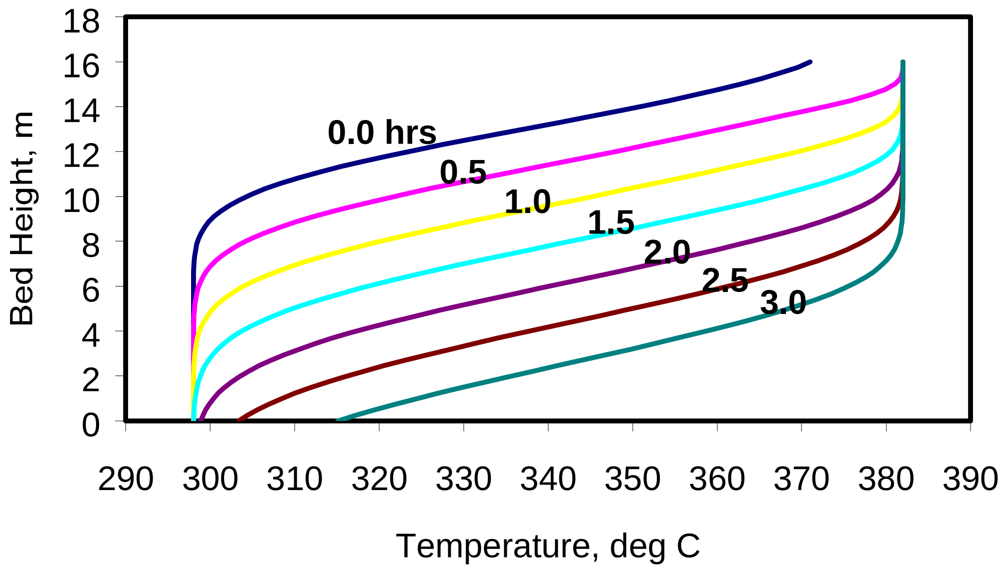
$$(\rho C_p)_f \varepsilon \frac{\partial T_f}{\partial \tau} = -\frac{(mC_p)_f}{A} \frac{\partial T_f}{\partial y} + h_v (T_b - T_f)$$

$$(\rho C_p)_b (1-\varepsilon) \frac{\partial T_b}{\partial \tau} = h_v (T_f - T_b)$$

Model Results







Thermal Gradient During Charging

Screening Potential Filler Materials in Nitrate Salt

- Seventeen commonly mined minerals and crushed rock were evaluated for their compatibility with nitrate salts
- The ideal filler material would have the following properties:
  - Inexpensive
  - Widely available
  - Low void fraction
  - Compatible with nitrate salts
  - Have a high heat capacitance

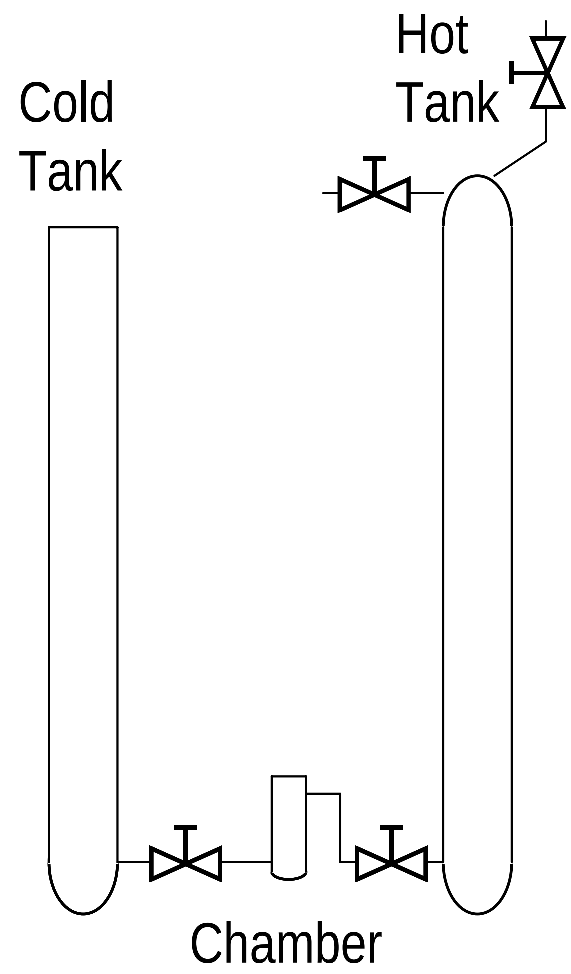
Chemical Name	Mineral Name	Chemical Formula
Aluminum oxide	Corundum	Al_2O_3
Aluminum oxyhydroxide	Bauxite*	$AlO_x(OH)_z$
Barium carbonate	Witherite	$BaCO_3$
Barium sulfate	Barite	$BaSO_4$
Calcium carbonate	Marble	$CaCO_3$
Calcium fluoride	Fluorite	CaF_2
Calcium sulfate	Anhydrite	$CaSO_4$
Iron (II,III) oxides	Taconite	Fe_2O_3,Fe_3O_4
Iron titanate	Ilmenite	$FeTiO_3$
Magnesium carbonate	Magnesite	$MgCO_3$
Silicon carbide	Carborundum	SiC
Tin oxide	Cassiterite	SnO_2
Calcium hydroxyphosphate	Hydroxylapatite	$Ca_5(PO4)_3$ OH
Calcium flurophosphate	Fluorapatite	Ca5(PO4)3F
Calcium carbonate	Limestone	$CaCO_3•H_2O$
Silicon dioxide	Quartzite	SiO_2

Isothermal Tests of Filler Materials

- Evaluated candidate materials in nitrate salts at 400 C. Samples were removed at 10, 100, 400 and 1000 hours of exposure.
- Samples were washed, weighed, and photographed. The salt was analyzed for contaminants.
- Results indicated the most promising materials were: quartzite, taconite, marble, NM limestone,apatite, corrundum, scheelite, and cassiterite.

Thermal Cycling Tests

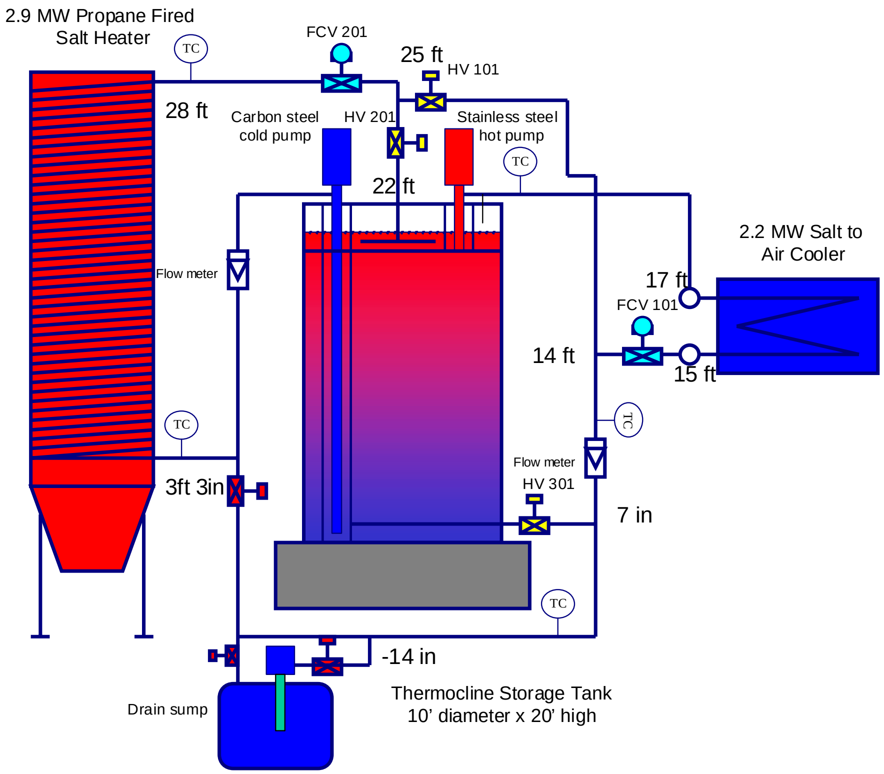
- Evaluated how well materials held up to thermal cycling condition expected in a thermocline system. At least 350 cycles between 290 and 400 deg C were conducted on each sample.
- Samples tested: taconite, marble, NM limestone, quartzite, and silica sand.
- Results:
  - NM Limestone fell apart
  - Marble softened and individual grains appeared to enlarge
  - Taconite pellets held together well. Absorbed some salt in pores
  - Quartzite rock and silica sand held up remarkable well and were selected as filler material for pilot-scale test



Thermal Cycling System

Thermocline Test

- Evaluate on a larger (pilot-scale) a molten-salt thermocline concept.
- Fabricated a 6 m tall by 3 m diameter carbon steel tank. Filled tank with a 2:1 mixture of quartzite rock and silica sand to a level of 5.2 m.
- Sodium nitrate and potassium nitrate were melted and added to tank.
- A propane heater simulated the heat input from the solar field (via the salt-to-oil heat exchanger).
- A forced-air cooler simulated heat rejection to the steam generator (through the salt-to-oil exchanger).



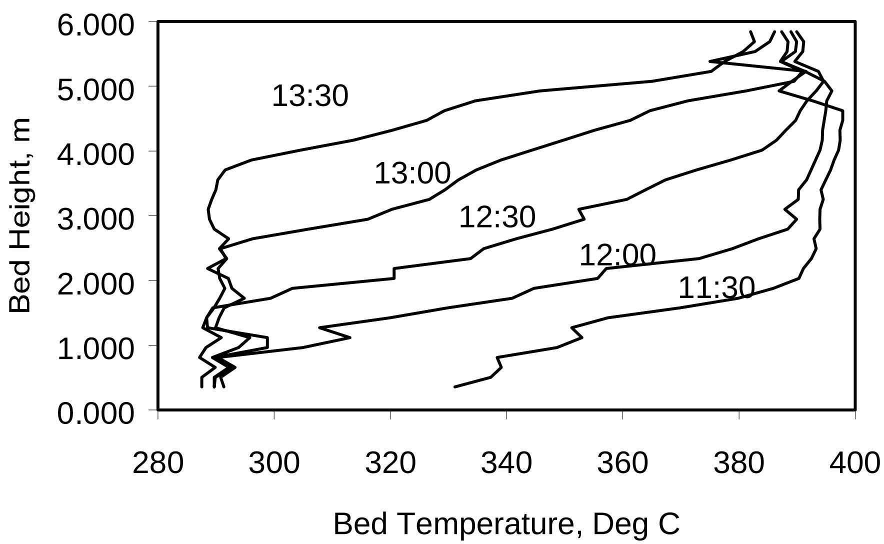
Tests Conducted

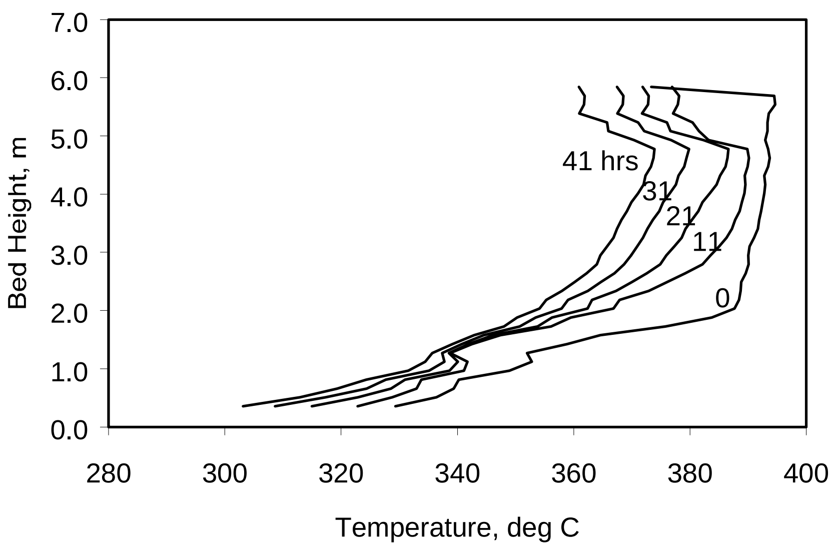
- Verification of heat capacity of system
- Evaluation of size and shape of thermal gradient
- Evaluation of change of shape of gradient over time
- Measurement of heat loss over time

Pilot-Scale Thermocline System

Thermocline Test Results

- Capacity measured to be 2.44 MWh (slightly higher than 2.3 MWh design estimate.)
- Height of gradient during charging matches modeled profile.
- Gradient tended to become more tapered after 41 hours, but can still yield useful energy at a reasonable temperature potential.
- Heat loss was higher than modeled (likely due to heat loss through pump penetrations at the top (which weren't modeled.)





Profile during discharging and stagnant with heat loss

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Economic Analysis for a 688 MWh_t Two-tank and Thermocline Systems

Component	Two-Tank Molten Salt	Thermocline with Quartzite
Nitrate Solar Salt, $k	11800	3800
Filler Material, $k	0	2200
Tank(s), $k	3800	2400
Salt-to-oil Heat Exchanger, $k	5500	5500
Total, $k	21100	13900
Specific Cost, $/kWh	**31**	**20**

Thermocline Molten-Salt System is 65% the cost of a Two-tank Molten-Salt System

Summary

- A molten salt thermocline system has been developed that is lower cost than a two-tank molten salt system.
- Isothermal and thermal cycling tests showed that silica sand and quartzite rock as well as taconite were compatible with nitrate salts.
- The feasibility of a molten-salt thermocline system was proven on a pilot scale 2.3 MWh storage system.